Hierarchically Acting Sterile Neutrinos

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We propose that a hierarchical spectrum of sterile neutrinos (eV, keV, 10^{13-15} GeV) is considered to as the explanations for MiniBooNE and LSND oscillation anomalies, dark matter, and baryon asymmetry of the universe (BAU) respectively. The scenario can also realize the smallness of active neutrino masses by seesaw mechanism.

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The compelling evidences from solar, atmospheric, reactor, and accelerator neutrino experiments have established the phenomenon of neutrino oscillations. The standard description is that the experimental data can be nicely explained by the mixings between the flavor and mass eigenstates of the three neutrinos in Standard Model (SM), the so-called "active" neutrinos. The unitary mixing matrix is parametrized in terms of three rotation angles (θ_{12}, θ_{23}, θ_{13}) and one Dirac CP violating phase δ_{CP}. The probabilities of flavor oscillations are governed by the θ_{ij} and two mass-squared differences $\Delta m^2_{12} \simeq 7.59\times10^{-5}\text{eV}^2$ and $|\Delta m^2_{31}| \simeq 2.45\times10^{-3}\text{eV}^2$ [1], where $\Delta m^2_{23} > 0$ or $\Delta m^2_{23} < 0$ refers to normal or inverted mass hierarchy spectrum respectively. One of the most famous approaches to generate the active neutrino masses is the so-called "Type-I seesaw mechanism", in which one adds N right-handed neutrinos $N_{R_i}(i = 1-N)$ to the SM and the active neutrino masses can be obtained by block diagonalizing the mass matrix of left and right handed neutrinos,

$$m_{\nu_{\alpha\beta}} = -\sum_{i=1}^{N} \frac{M_{D_{\alpha i}} M^T_{D_{i\beta}}}{M_{R_i}}. \tag{1}$$

Here $\alpha, \beta = e, \mu, \tau$ represent the flavor indices of the SM fermions, M_D is the Dirac mass matrix formed through the Yukawa interactions between left- and right-handed neutrinos, and M_{R_i} are the Majorana masses of right-handed neutrinos. Since the right-handed neutrinos are completely neutral under the SM gauge symmetries, the Majorana mass M_R is a gauge invariant quantity and N_{R_i} are often termed "sterile" neutrinos. At least two sterile neutrinos are needed to accommodate the two mass splits observed experimentally. The mass scales of $M_{D_{\alpha i}}$ and M_{R_i} are free parameters and cannot be fixed by oscillation experiments alone.

There are, however, results from the LSND [2] and the MiniBooNE [3] which cannot be accommodated in three active neutrinos description and may need to introduce one or more sterile neutrinos at the eV scale to fit the data (e.g. see [4, 5]). It should be mentioned that the light sterile neutrinos are also welcome in order to have successful Big Bang Nucleosynthesis (BBN) [6, 7], and are consistent with the preference for additional relativistic degrees of freedom, $N_{eff} = 4.34^{+0.86}_{-0.88}$, observed from the current cosmic microwave background (CMB) anisotropy probe and the large-scale structure (LSS) data [1].

Meanwhile, there is an increase in the amount and precision of cosmological data indicates that about 80% of the matter content in the universe is non-baryonic dark matter (DM). The study of nature of DM is one of the main topics in cosmology, astrophysics, and particle physics. The Cold Dark Matter (CDM) is widely studied partly because the WIMP (weakly interacting massive particle) may reveal its signal at LHC and is predicted in many popular models (supersymmetric models, etc). However, it has been noticed that a sterile neutrino with mass at the keV scale and with small mixing to the active neutrinos can make up the DM in the form of Warm Dark Matter (WDM) [8, 9]. Additionally, it was pointed out that the keV sterile neutrino might play an important role in explaining the pulsar kicks [10].

Finally, the level of one out of ten billions excess in the amount of matter over antimatter is a long standing puzzle for high energy physicists. The observation hints that baryon number (B) and/or lepton number (L) are violated in certain physical processes. Grand unified theories (GUTs) naturally provide a framework for breaking B and L, in which the fundamental fermions - quarks and leptons - are arranged in the same multiplets, and the out-of-equilibrium decays of heavy gauge bosons or colored Higgs bosons H_C will generate the sufficient baryon asymmetry around the scale of grand unification [11–15]. It was then recognized that the Standard Model (SM) violates $B + L$ symmetry through the $SU(2)_L$ global anomaly [16]. The process is not suppressed during the period 100 GeV $\lesssim T \lesssim 10^{12}$ GeV, and the solution is called "sphalerons" [17]. The sphaleron effect violates $B + L$ but conserves $B - L$, and therefore, it would erase any primordial $B + L$ asymmetry. We notice that any grand unification theories with higher symmetries respects $B - L$ symmetry. For example, $B - L$ is a global symmetry for $SU(5)$ GUTs and a local symmetry for $SO(10)$ GUTs respectively. The GUT-baryogenesis,

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TABLE I: The content of three sterile neutrinos models

Models	eV	keV	GeV	≫EW
νMSM		N_{R_1}	N_{R_2}, N_{R_3}	
Split Seesaw		N_{R_1}		N_{R_2}, N_{R_3}
BRZ	N_{R_1}, N_{R_2}	N_{R_3}		
HASN	N_{R_1}	N_{R_2}		N_{R_3}

therefore, is not able to explain baryon asymmetry in our universe (BAU). To solve the problem one has to generate $B-L$ asymmetry by violating pure baryon number [18] or by violating pure lepton number [19] (leptogenesis, e.g.), and the sphaleron process will convert partially $B-L$ asymmetry into baryon asymmetry. We adopt the construction that one heavy sterile neutrino causes lepton asymmetry during the epoch the sphalerons are ineffective, and the late decay of colored Higgs will generate the observed BAU.

We consider a scenario of three sterile neutrinos $N_{R_{i(i=1-3)}}$ with hierarchical mass spectrum (M_{R_1} ∼eV, M_{R_2} ∼keV, $M_{R_3} \sim 10^{13-15}$ GeV), in which the lightest one may help to explain the neutrino oscillation anomalies, keV-scale sterile neutrino is the candidate of dark matter, and the heaviest state N_{R_3} would resurrect the GUT-baryogenesis. Three sterile neutrinos can be introduced to cancel the additional gauge anomaly for any theory beyond SM with extra gauge $U(1)_{B-L}$ symmetry. We show this hierarchical spectrum of sterile neurinos simultaneously satisfy the observations, and how our scenario fits in the framework of GUT theories.

It has been proposed that models of SM with (three) additional sterile neutrinos are phenomenologically viable [20–22]. The so-called νMSM (ν Minimal Standard Model) [20], in which a mass of a keV sterile neutrino is responsible for DM, and two heavier states with degenerate masses lain in the range 1 GeV ∼ 100 GeV are required to be in thermal equilibrium around electroweak scale in order to generate BAU through the resonant neutrino oscillations. The split seesaw model with three sterile neutrinos living in the extra dimension (ED) is shown to be able to solve DM and BAU as well [21]. By utilizing an exponential factor in the size of ED one can split the Majorana masses of N_{R_i} with relative mild parameters associated to their locations in ED. Recently a flavor symmetry model [22] proposed by Barry, Rodejohann, and Zhang (BRZ), it consists of two $N_{R_{1,2}}$ masses at eV-scale and one N_{R_3} at keV-scale. The two eV-scale sterile neutrinos are used to explain LSND and MiniBooNE anomalies while the keV sterile neutrino is the WDM particle. The scenarios are summarized in Table I. These setup can answer two of the three puzzles we mentioned above while our hierarchically acting sterile neutrinos (HASN) scenario would explain the three puzzels simultaneously. The splittings of the sterile neutrino masses can be achieved by implementing split seesaw mechanism [21] or Froggatt-Nielsen (FN) mechanism [23] to the model.

The Lagrangian which is relevant to neutrino masses has the form

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\rm SM} + i\bar{N_{R_i}}\;\partial\!\!\!/ N_{R_i} - y_{\alpha i} H^\dagger \bar{l}_\alpha N_{R_i} \\ &\quad - \frac{M_{R_i}}{2}\bar{N}^c_{R_i} N_{R_i} + \text{h.c.} \end{aligned} \qquad (2)$$

Here $\mathcal{L}_{\rm SM}$ is the SM Lagrangian, l_α are $SU(2)_L$ leptonic doublets with flavor index α, H is SM Higgs, $y_{\alpha i}$ are the Yukawa couplings, and c is charged conjugation. The Majorana mass matrix of sterile neutrinos is chosen to be diagonal without loss of generality. The 6×6 neutrino mass matrix is given in the form

$$\begin{pmatrix} 0 & M_D \\ M_D^\dagger & M_R \end{pmatrix} \qquad (3)$$

in the basis $(\nu_e, \nu_\mu, \nu_\tau, N_{R_1}, N_{R_2}, N_{R_3})$, and $M_R = {\rm diag}(\mathcal{O}({\rm eV}), \mathcal{O}({\rm keV}), \mathcal{O}(10^{13-15}){\rm GeV})$. Here we give a brief comment on a realization of such a hierarchical mass spectrum of right-handed neutrinos. One of simple examples to realize it is to utilize the split seesaw mechanism, in which the spinor fields are introduced in a flat five dimensional (5D) spacetime whose compactification length of extra dimension is ℓ and all SM particle are assumed to live in a 4D-brane. After solving the 5D Dirac equation and identifying the zero-modes of the 5D spinors with the right-handed neutrinos, the effective (4D) right-handed Majorana masses are described by exponential functions as $M_{Ri} = 2\kappa_i m_i v_{B-L}/(M(e^{2m_i\ell}-1))$ where κ_i, m_i, $v_{\rm B-L}$, and M are a coupling constant of order one, bulk masses for 5D spinors, $U(1)_{B-L}$ breaking scale, and 5D fundamental scale respectively. In this mechanism, one can easily obtain a hierarchical right-handed neutrino mass spectrum such as $(M_{R_1}, M_{R_2}, M_{R_3}) = (1\text{ eV}, 1\text{ keV}, 10^{13}\text{ GeV})$ within a set of moderate parameters when one takes $\kappa_i = 1$, $v_{\rm B-L} = 10^{15}$ GeV, and $(M\ell, m_1\ell, m_2\ell, m_3\ell) = (30, 27.9, 24.4, 1.03)$ as reference values. The FN mechanism can also give a hierarchical mass spectrum with appropriate $U(1)_{\rm FN}$ charges.

After electroweak symmetry breaking where Higgs develops its vacuum expectation value (VEV) $v = 174$ GeV, one gets Dirac neutrino mass terms. The left-handed neutrinos receive their Majorana masses through seesaw mechanism, we obtain

$$m_{\nu_3} \sim \begin{cases} m_{atm} \simeq \frac{|y^*_{\alpha 3} y_{\beta 3}| v^2}{M_{R_3}} & \text{for NH} \\ \epsilon \simeq \frac{|y^*_{\alpha 2} y_{\beta 2}| v^2}{M_{R_2}} & \text{for IH} \end{cases}, \qquad (4)$$

$$m_{\nu_2} \sim m_{sol} \simeq \frac{|y^*_{\alpha 1} y_{\beta 1}| v^2}{M_{R_1}} \quad \text{for both NH and IH}, \qquad (5)$$

$$m_{\nu_1} \sim \begin{cases} \epsilon \simeq \frac{|y^*_{\alpha 2} y_{\beta 2}| v^2}{M_{R_2}} & \text{for NH} \\ m_{atm} \simeq \frac{|y^*_{\alpha 3} y_{\beta 3}| v^2}{M_{R_3}} & \text{for IH} \end{cases} \qquad (6)$$

at the leading order, where NH and IH mean the normal hierarchy and inverted hierarchy respectively. The

indices α and β in m_{ν_3} for NH should correspond to only μ and τ in order to be consistent with the current data of neutrino oscillation experiments, that is, there are a maximal atmospheric, a large solar, and a small reactor mixing angles. By choosing a set of appropriate values of the Yukawa couplings, the experimentally observed mixing angles can be always fitted in our scenario. The degenerated mass spectrum of active neutrinos can be also realized.

The dark matter candidate of the scenario is decaying DM. The keV sterile neutrino N_{R_2} should live longer than the age of the universe and can be estimated as $\tau_{N_{R_2}} \simeq 5\times 10^{26}(M_{R_2}/\mathrm{keV})^{-5}(10^{-8}/\Theta^2)$s, here Θ is the mixing between keV sterile neutrino and active neutrinos. The generic way to produce DM is through the active-sterile neutrino oscillations [8], however, the abundance is constrained by the X-ray observations [24] (also see [25] and references therein), structure formation simulations, and the Lyman-α bounds [26]. One way to relax the restrictions was proposed by Shi and Fuller [9] that an enhancement of the production of keV sterile neutrino can be realized via lepton-number-driven MSW (Mikheyev-Smirnov-Wolfenstein) effect. The other possibility is the N_{R_2} pair production via $U(1)_{\mathrm{B-L}}$ gauge boson exchange [21]. It has been shown that as long as the reheating temperature is about 10^{13} GeV one can account for the relic abundance of DM. The corresponding Yukawa couplings of sterile neutrino DM for the required mass $\mathcal{O}(1)$ keV$\lesssim M_{R_2} \lesssim \mathcal{O}(10)$ keV are typically restricted to $\mathcal{O}(10^{-15}) \lesssim |y_{\alpha 2}| \lesssim \mathcal{O}(10^{-13})$ to satisfy astrophysical constraints (see e.g. [25] and references therein). This means that terms from the sterile neutrino DM through the seesaw mechanism does not contribute to the atmospheric and solar neutrino mass scales shown in (4)-(6). The Yukawa couplings for the 1st and 3rd generations of right-handed neutrinos are approximated as $|y^*_{\alpha 3}y_{\beta 3}|^{1/2} \sim \mathcal{O}(0.1)$ and $|y^*_{\alpha 1}y_{\beta 1}|^{1/2} \sim \mathcal{O}(10^{-13}$-$10^{-12})$ to satisfy the atmospheric and solar scales with $(M_{R_1}, M_{R_3}) = (1\ \mathrm{eV}, 10^{13}\ \mathrm{GeV})$ respectively. It is seen that the construction of active neutrino mass spectrum in HASN scenario is consistent with the constraints on keV sterile neutrino DM. It can be also found that the atmospheric scale can be derived from the ratio of the right-handed neutrino mass, $M_{R_3} \sim \mathcal{O}(10^{13})$ GeV, and the corresponding Dirac masses, $|y^*_{\alpha 3}y_{\beta 3}|^{1/2}v \sim \mathcal{O}(10)$ GeV, when N_{R_3} gets integrated out. While the solar scale comes from the seesaw relation between $M_{R_1} \sim \mathcal{O}(1)$ eV and $|y^*_{\alpha 1}y_{\beta 1}|^{1/2}v \sim \mathcal{O}(0.1)$ eV. Finally, the ratio of mass scales between the 2nd generation of sterile neutrino (DM), $M_{R_2} \sim \mathcal{O}(1)$ keV, and the corresponding Dirac masses, $|y^*_{\alpha 2}y_{\beta 2}|^{1/2}v \sim \mathcal{O}(10^{-3}$-$10^{-1})$ eV, is too steep to contribute to the active neutrino mass (atmospheric and solar) scales. Therefore, the sterile neutrinos are hierarchically acting also for giving the active neutrino mass scales. The Yukawa structure realizing the scenario can be obtained in both split seesaw and FN mechanisms with appropriate model parameters.

Now we come to the phenomena of neutrino oscillation anomalies. The LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions anomaly reported a 3.8σ excess of $\bar{\nu}_e$ candidate events, in which the neutrino fluxes were produced by dumping 800 MeV protons into a "beam stop" which mostly generate π^+, and neutrinos (anti-neutrinos) are the decay products of pions. The probability that ν_a oscillates into ν_b is given by $P(ab) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E})$, where θ is the mixing angle, L is the neutrino travel distance in the unit of meter, and E is the neutrino energy in MeV. The typical anti-neutrinos energies are a few MeV for reactor experiments, the excess is interpreted as the hints for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation with $\Delta m^2 \sim 1$ eV^2. This indicates at least one sterile neutrino with mass at the eV-scale. Then the MiniBooNE experiment set out to check the excess events in the $\nu_\mu \to \nu_e$ transitions and found the parameters were not compatible with LSND [27]. However, more recently the MiniBooNE accumulated more anti-neutrino oscillation data and reported the excess electron anti-neutrino appearance is reconciled with LSND results [3]. To accommodate the neutrino and anti-neutrino data the additional CP violation has to be invoked. One simple way is to add two sterile neutrinos at eV scale (the so-called (3+2) scheme) to neutrino sector, the CP violation at short-baselines would let to reconcile both LSND and MiniBooNE results [4, 5, 28–30]. In our scenario a (3+1) scheme together with nonstandard interactions (NSI) of neutrinos will allow to fit the data [4]. The new interactions may modify the charged and neutral currents, and provide the new sources of CP violation. They may affect the neutrino oscillations via the production, propagation, and the detection processes. The four-fermion operators can be expressed at low energies as

$$\mathcal{L}_{\mathrm{NSI}} = 2\sqrt{2}G_F \sum_f \epsilon^{f_{L,R}}_{\alpha\beta}(\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{f}_{L,R}\gamma_\mu f_{L,R}) + \mathrm{h.c.}, \quad (7)$$

where G_F is Fermi constant, f represents fermions (charged leptons and quarks), and α, β are flavor indices, and L, R are chiralities. The new interactions can be induced from several possibilities of physics beyond SM. For example, in GUT theories the $\psi(\mathbf{10}) \oplus \psi(\bar{\mathbf{5}})$ fermion representations of $SU(5)$ are coupled to a $\mathbf{5}(H_C)$ and a $\bar{\mathbf{5}}(\bar{H}_C)$ representation of Higgs, and the Yukawa interactions read $\mathcal{L}_Y = \psi(\mathbf{10})^T \lambda^u \psi(\mathbf{10}) H_C + \psi(\mathbf{10})^T \lambda^d \psi(\bar{\mathbf{5}})\bar{H}_C$. It has been shown that one can fit to global short-baseline data for $\epsilon_{\alpha\beta} \sim \mathcal{O}(10^{-2})$ [4].

In the context of our consideration, we adopt that a sterile neutrino N_{R_3} is heavier than the colored Higgs bosons, and a lepton number violating interaction $l\phi l\phi/(2M_{R_3})$, here ϕ is the Higgs doublet, keeps in thermal equilibrium when $T \gtrsim 10^{12}$ GeV. Therefore, all lepton asymmetry generated by colored Higgs decay is erased by the process $l + \phi \to \bar{l} + \phi^\dagger$ while the generated baryon asymmetry remains intact, and so $B - L \neq 0$ can be satisfied. When temperature drops below 10^{12} GeV the sphaleron transitions become effective, as the results, the produced baryon asymmetry is partially converted into the lepton asymmetry but a residual baryon asymmetry remains, and thus the observed

BAU can be generated. In the case of $SU(5)$ GUT we have the Yukawa couplings $\psi(\mathbf{10})^T\lambda^{u(k)}\psi(\mathbf{10})H_C^{(k)}$ and $\psi(\mathbf{10})^T\lambda^{d(k)}\psi(\bar{\mathbf{5}})\bar{H}_C^{(k)}$ $(k=1,2)$. The size of BAU is calculated as [15, 19, 31, 32]

$$Y_{\Delta B} \equiv \frac{n_B - n_{\bar{B}}}{s} = 0.35\cdot 0.5\cdot 10^{-2}\cdot\frac{\epsilon_B}{1+(3K)^{1.2}}, \quad (8)$$

where $K \equiv \frac{1}{2}\frac{\Gamma}{H}|_{T=m_{H_C}} \simeq \frac{1.1\times 10^{18}\text{ GeV}}{\lambda^{u2}m_{H_C}}\left(\frac{1}{g_*}\right)^{1/2}$ is the washout factor and $\epsilon_B \simeq \frac{\eta_1}{8\pi}\cdot 10^{-2}[F(x)-F(1/x)+G(x)-G(1/x)]$ is the CP-asymmetry with Γ, H, m_{H_C}, g_*, x are the decay rate, expansion rate, colored Higgs mass, degrees of freedom $g_*|_{T\simeq m_{H_C}} \simeq 53$, mass ratio $m^2_{H_C^{(2)}}/m^2_{H_C^{(1)}}$, respectively. The functions F and G are defined as $F(x)\simeq 1-x\ln\left(\frac{1+x}{x}\right)$ and $G(x)=\frac{1}{x-1}$. The factor 0.35 comes from the sphaleron process, and we take $\eta_1 = \sin(\arg[\mathrm{tr}(\lambda^{d(1)\dagger}\lambda^{d(2)}\lambda^{u(1)\dagger}\lambda^{u(2)})])$ and $\eta_1\simeq\eta_2$. It is seen that we can realize $Y_{\Delta B} = 8.75\times 10^{-11}$ when we set $(m_{H_C^{(1)}}, m_{H_C^{(2)}}) = (9\times 10^{12}, 8\times 10^{12})$ GeV and $\eta_1 \simeq -0.444$. These values are consistent with this baryogenesis scenario and above discussion of the right-handed neutrinos mass spectrum, that is, 10^{12} GeV $\leq m_{H_C^{(i)}} < M_{R_3} \lesssim 10^{15}$ GeV. A heavier mass of the corresponding sterile neutrino as 10^{14-15} GeV is also possible for this baryogenesis.

The hierarchical spectrum of sterile neutrinos (eV, keV, 10^{13-15} GeV) is a simple and economical scenario, especially it can be embedded in many frameworks beyond SM. In light of the puzzles from neutrino oscillation anomalies, dark matter, and baryon asymmetry of the universe (BAU) we have shown that this scenario is phenomenologically viable. Searching for deviations from standard three active neutrino oscillations and the X-ray astronomy will offer opportunity to test the scenario.

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